

# 10 pc Scale Circumnuclear Molecular Gas Imaging of Nearby AGNs

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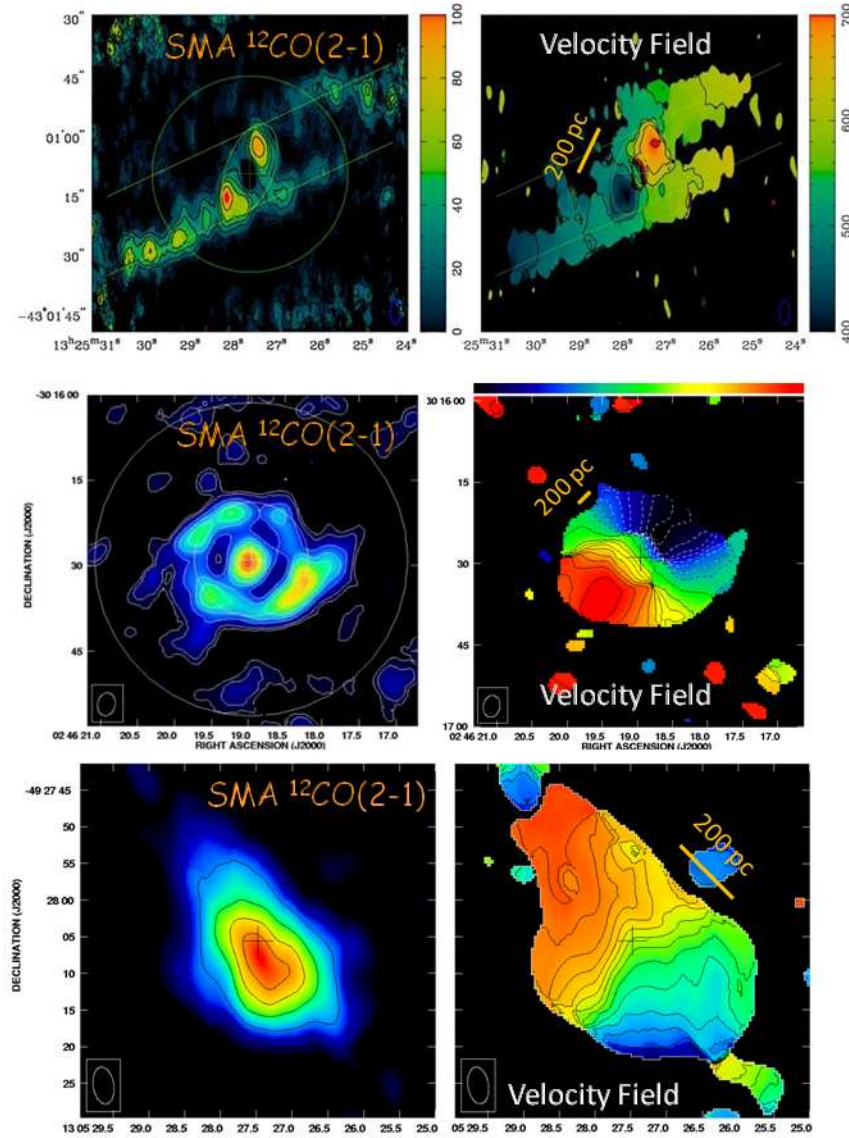
**Abstract.** We present the images and kinematics of circumnuclear molecular gas from 100 pc scale down to 10 pc scale in nearby active galactic nuclei (AGNs) using the Submillimeter Array (SMA) and the Plateau de Bure Interferometer (PdBI). We have observed several nearby galaxies that host AGNs, such as the nearest radio galaxy Centaurus A (NGC 5128), the Seyfert 2 galaxy M51 (NGC 5194), the Seyfert 2 galaxy NGC 1068, the Seyfert 1 galaxy NGC 1097, and the Seyfert 2 / starburst composite galaxy NGC 4945, in CO lines to see whether the molecular gas distribution, kinematics, and physical conditions at 10 – 100 pc scale follows the AGN unified model or not. In 100 pc scale, most of the circumnuclear molecular gas shows smooth velocity gradient, suggesting a regular rotating feature, and also shows abnormal line ratios, suggesting the existence of active sources to make the circumnuclear molecular gas dense and/or warm conditions or abnormal chemical compositions. In 10 pc scale, on the other hand, the molecular gas kinematics shows various characteristics, some shows very disturbed kinematics such as a jet-entrained feature in the galaxies that have jets, but some still shows regular rotation feature in a galaxy that does not have obvious jets. These results indicate that the kinematics and physical/chemical conditions of the circumnuclear molecular gas at the scale less than 100 pc is highly affected by the AGN activities, and at this scale, there is no clear evidence of any unified feature seen in the circumnuclear molecular gas.

## 1. Introduction

It was well known for a long time that there are two types of active galactic nuclei (AGNs) at the centers of galaxies based on optical spectra: Type 1 AGNs show broad permitted lines as well as narrower forbidden lines, and type 2 shows relatively narrower permitted and forbidden lines [1]. In 1985, Antonucci and Miller [2] published a result of a polarization observation toward the nucleus of the type 2 AGN host galaxy NGC 1068, showing that broad permitted lines have been observed in the polarized (i.e., scattered) light, suggesting that the type 1 AGN is hidden behind the dense obscuring material in this type 2 nucleus. This result has led to the AGN unification model, which is, the broad line region is located close to a supermassive black hole of a galaxy surrounded by a dense obscuring torus, and it will be type 1 if one sees from the pole of the torus, and will be type 2 if one sees through the torus [3, 4].

## 2. Circumnuclear Molecular Gas Distribution at 100 pc Scale

After the suggestion of the AGN unification model, intense searches of the obscuring torus have been started, especially using millimeter-wave interferometers. Jackson *et al* [5] and Kohno *et*



**Figure 1.** CO(2-1) integrated intensity (moment 0; left) and intensity-weighted velocity field (moment 1; right) maps of *Above:* Centaurus A [11], *Middle:* NGC 1097 [9], and *Bottom:* NGC 4945 [10]. All the images were obtained with the SMA. The linear scale of 200 pc is shown as a bar in the velocity field map of each galaxy.

*al* [6] observed nearby Seyfert 2 galaxies NGC 1068 and M51 (NGC 5194), respectively, with the HCN(1-0) line at a spatial resolution of several arcseconds, and successfully imaged the dense gas around the AGNs with the velocity gradients almost perpendicular to the radio jets. These results can be explained as dense gas disks or tori with the radii of a few hundred pc, rotating around the AGNs perpendicular to the radio jets. Furthermore, the column density of the observed molecular gas of a few  $\times 10^{23} \text{ cm}^{-2}$  [6] was consistent with that measured as the absorption column density in the X-ray observations of  $(4.2 \pm 1.5) \times 10^{23} \text{ cm}^{-2}$  [7]. These results matched very well with the AGN unification model.

Since the Submillimeter Array (SMA) [8] has started scientific observations, we have started to observe nearby AGNs in the higher transition ( $J=2-1$  and/or  $3-2$ ) CO lines at the spatial resolutions of around a few hundred pc. We observed the galactic centers (central a few kpc) of the Seyfert 1 galaxy NGC 1097 [9], the Seyfert 2 / starburst composite galaxy NGC 4945 [10], and the nearest radio galaxy Centaurus A (NGC 5128) [11] with the CO(2-1) line, and the obtained images are shown in Figure 1. All these galaxies have central molecular gas concentrations

with the scale of several hundred pc (note that Centaurus A has strong absorption features at the galactic center, so that the image shows a hole at the nucleus [12]), and the velocity fields exhibit smooth velocity gradient, namely rigid rotation feature, around the nucleus (note that NGC 4945 is an edge-on galaxy with a bar, so that the velocity field around the nucleus is affected by the non-circular motion [13]). These velocity features again suggest rotating gas disks or tori with the radii of a few hundred pc, similar as those observed in NGC 1068 and M51 mentioned above. Since the kinematics of these galaxies shows the rigid rotation feature, the gravitational fields of all these galaxies are dominated by the bulge, not the supermassive black holes in the AGNs.

On the other hand, we also obtained higher-J CO lines toward the central a few kpc regions of NGC 1068 [14], NGC 1097 [9, 15], and M51 [16], and compared with the previously observed lower-J CO line images (Figure 2). Central molecular condensations can be seen in all the images (in whatever transitions) presented here, but the intensities are stronger in higher-J lines than lower-J lines, indicating that the circumnuclear molecular gas has either higher densities and/or higher temperature conditions than, or abnormal chemical conditions compared to the molecular gas at outer radii. Lines ratios at outer radii, namely at the spiral arm regions or at the starburst ring, have similar values as those regions in other galaxies, so that this abnormal line ratios are obviously affected by the existence of the AGNs.

These results suggest that the AGN activities *do not* affect the kinematics of the circumnuclear molecular gas at 100 pc scale, but *do* affect the physical/chemical conditions of the circumnuclear molecular gas.

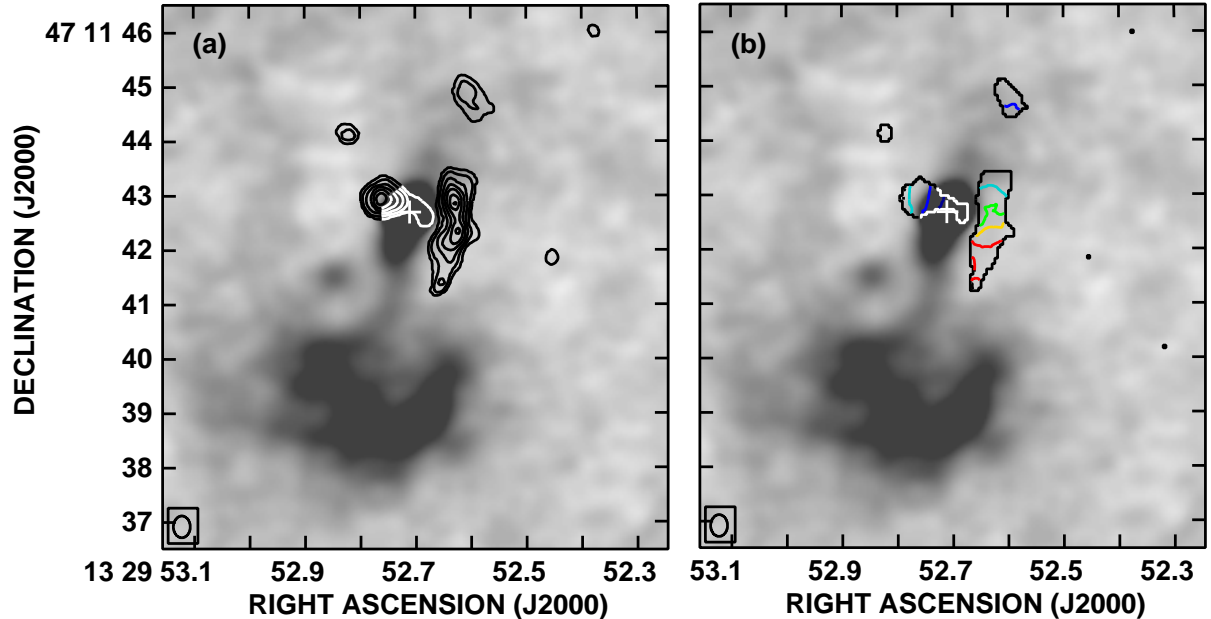
### 3. Circumnuclear Molecular Gas Distribution at 10 pc Scale

In our SMA M51 CO(3-2) data presented above, we noticed that the kinematics of the circumnuclear molecular gas deviates from the circular rotation as suggested before [16], but could not study in detail due to the limited (large) spatial resolution. We therefore observed the circumnuclear molecular gas of M51 with  $\sim 10$  pc spatial resolution to spatially resolve the gas kinematics around the Seyfert 2 nucleus in this galaxy. We used the new-A (newly extended) configuration (maximum baseline length = 760 m) of the IRAM Plateau de Bure Interferometer (PdBI), and observed with the CO(2-1) line, since the CO(2-1) line flux is higher than that of the CO(1-0) line, and it is possible to obtain higher spatial resolution images.

Figure 3 shows the newly obtained circumnuclear CO(2-1) image of M51 [21]. The spatial resolution reached to  $0.41'' \times 0.31''$ , which corresponds to the linear scale of  $14 \text{ pc} \times 11 \text{ pc}$  at the distance of M51 (7.1 Mpc [22]). Figure 3(a) is the integrated intensity map of the CO(2-1) data. As you can see, there are mainly two molecular gas clouds at the eastern and western sides of the nucleus, perpendicular to the radio jets. The cloud at the western side is elongated along north-south direction, almost parallel to the radio jets, with the projected distance to the nucleus of only  $\sim 30$  pc. The one at the eastern side only has one strong peak with the size of about 30 pc ( $\sim 1''$ ), roughly the size of the typical Giant Molecular Cloud (GMC) in our Galaxy. There is a weak emission extending toward the nucleus from this cloud. The column density of the molecular gas in front of the nucleus calculated from this weak emission is very small, only  $6.2 \times 10^{21} \text{ cm}^{-2}$ , much smaller than the column density of atomic gas derived from the recent X-ray absorption measurements of  $5.6 \times 10^{24} \text{ cm}^{-2}$  [24]. The missing flux due to our interferometric observations cannot explain this difference; this is because the amount of the detected flux has to be at the order of only 0.1% of the total flux for explaining the difference with the missing flux, but our observation obviously detected much more than this flux level. This suggests that the absorbing material in front of the X-ray source (i.e., AGN) is much smaller than our beam size of  $\sim 10$  pc.

Figure 3(b) is the intensity-weighted velocity field map of the CO(2-1) data. The eastern cloud exhibits the velocity gradient from west (blueshift) to east (redshift). This direction of





**Figure 3.** CO(2-1) (a) integrated intensity (moment 0) and (b) intensity-weighted velocity field (moment 1) maps of M51 at  $0.41'' \times 0.31''$  (14 pc  $\times$  11 pc) resolution [21] overlaid on the VLA 6 cm radio continuum grayscale image [23]. The cross in each figure marks the position of the AGN.

from north (blueshift) to south (redshift), namely the velocity gradient along the radio jets. The amount of the velocity gradient of the western cloud is  $2.2 \pm 0.3 \text{ km s}^{-1} \text{ pc}^{-1}$ , which is consistent with that of the ionized gas along the radio jets [25]. These distribution and the kinematics of the western cloud together with the kinematics of the ionized gas along the radio jets suggest that the western cloud is entrained by the radio jets [21]. Note that if we smooth our CO(2-1) data to ten times larger spatial resolution, the kinematics is consistent with that of the past observations [6], since the average velocities of the eastern and the western clouds are consistent with the blueshifted and the redshifted velocities, respectively, of the past observations.

In summary, our  $\sim 10 \text{ pc}$  spatial resolution CO(2-1) results show that there is no clear evidence of rotating disk or torus around the Seyfert 2 nucleus of M51 as suggested in the past, but exhibit that there are highly disturbed molecular gas features very close to the nucleus, possibly affected by the AGN activities. Furthermore, the obscuring material of this type 2 AGN has the size much smaller than our beam size of  $\sim 10 \text{ pc}$ .

Such disturbed circumnuclear gas near AGNs is also recently suggested in NGC 1068 [19]: Recent multiple molecular line observations toward the nucleus of NGC 1068 at a spatial resolution of  $\sim 30 \text{ pc}$  with the SMA and the PdBI revealed that the circumnuclear molecular gas kinematics is better explained by a rotation with an outflowing motion, rather than by a warped disk as suggested in the past [26]. The radius of the rotating disk is estimated to be around 60 pc. The molecular outflow is suggested to be flowing along the radio jets and the ionization cone with the velocity gradient of  $3 \text{ km s}^{-1} \text{ pc}^{-1}$ , similar to that observed in the jet-entrained molecular gas in M51 (see above).

On the other hand, a circumnuclear molecular gas disk without any disturbance has also been observed: Recent CO(2-1) observation toward NGC 4945 at a spatial resolution of  $\sim 20 \text{ pc}$  with the SMA has displayed a circumnuclear molecular gas disk with no disturbance in the kinematics (i.e., rigid rotation feature in the position-velocity diagram) [27]. The radius of the



rotating disk is around 20 pc, which is closer to the AGN than the distance of the circumnuclear clouds of M51 as mentioned above. Note that NGC 4945 does not have any obvious jet from its Seyfert 2 nucleus, in contrast to the nuclei of M51 and NGC 1068 that exhibit radio and/or ionized gas jets.

#### 4. Discussion

We only have three observations of the circumnuclear molecular gas in  $\sim 10$  pc spatial resolution, but all the samples show different features. The circumnuclear gas of M51 does not show any evidence of clear rotation feature, but show totally disturbed kinematics due to the radio jets. That of NGC 1068 exhibits rotation feature with outflowing gas along the radio jets, but in the case of NGC 4945, which does not have obvious jets from the AGN, only rotation feature can be seen. These results suggest that the jet activity from the AGN affects the circumnuclear molecular gas around  $\sim 10$  pc scale, which could not be seen at  $\sim 100$  pc scale. This suggests that there is no clear unified feature in the circumnuclear molecular gas around AGNs at the scale of 10 pc. Together with the line ratio anomaly, which means the physical conditions or chemical composition anomaly, in the circumnuclear molecular gas as mentioned above, the circumnuclear molecular gas close to AGNs is suggested to be highly affected by the AGN activities.

This also suggests that the star formation near AGNs can be highly affected by the AGN activities; for instance, AGNs with strong jet activities can have less star formation in the circumnuclear (within 100 pc) regions, since too large turbulence induced by the jet activities. Due to very limited sample we have, it is difficult to say anything about this kind of possibilities, but if we increase samples (with ALMA for example), we may be possible to provide some hints for the AGN-starburst connection.

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